U.S. Department of Energy

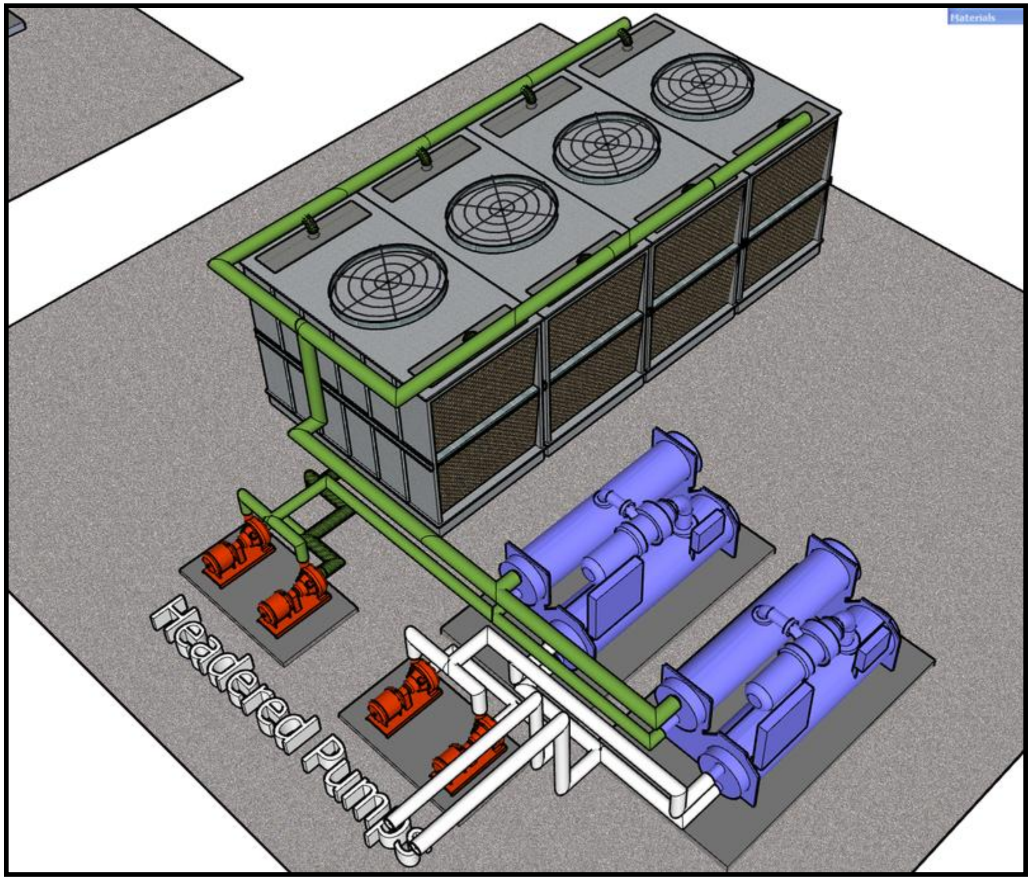
Energy Efficiency and Renewable Energy

DATA CENTER ENERGY EFFICIENCY TRAINING

Central Chilled-Water Plant

<Presenter>

Chilled-Water Plant



Optimizing Energy Usage

- Chillers
  - Type, efficiency, size, VSD
- Cooling Towers
  - Fan type, efficiency, approach, range, speed control, flow turndown
- Chilled Water Pumps
  - Arrangement, flow rate (delta-T), pressure drop, VSD
- Condenser Water Pumps
  - Flow rate (delta-T), pressure drop
- Air Handling Units
  - Coil sizing, air-side pressure drop, water-side pressure drop

Pop Quiz 1

- What happens to component energy usage if we lower CWS setpoint?
  - Chiller
  - Towers
  - Pumps

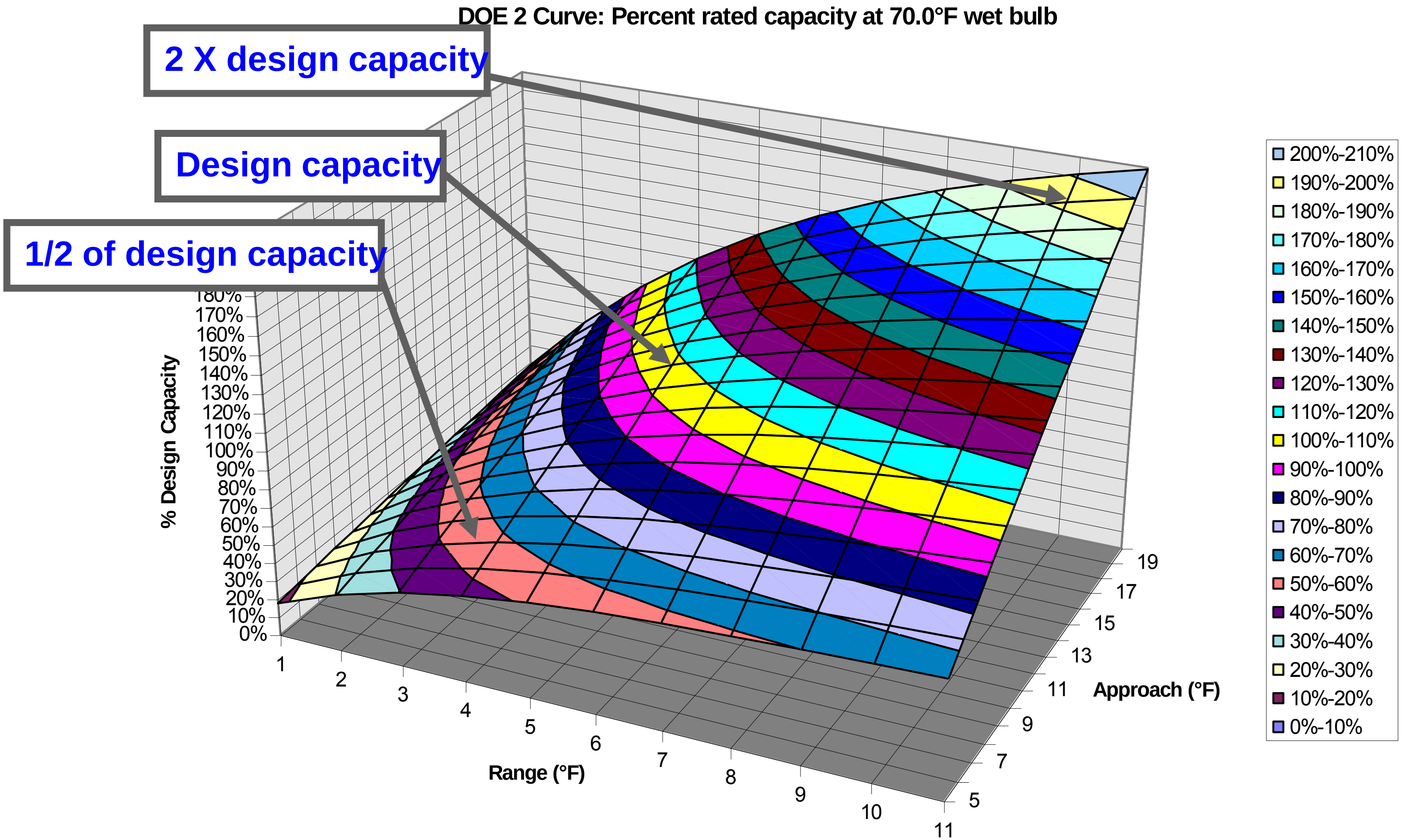
Pop Quiz 2

- What happens to component energy usage if we lower CW flow?
  - Chiller
  - Towers
  - Pumps

Optimizing CHW Plant Design

- Ideal: Design a plant with lowest life cycle costs (first cost plus lifelong operating costs) accounting for all the complexities and interaction among plant components
- Practical: Design plant subsystems to be near-life cycle cost optimum using techniques that are simple and practical enough to be used without a significant increase in design time

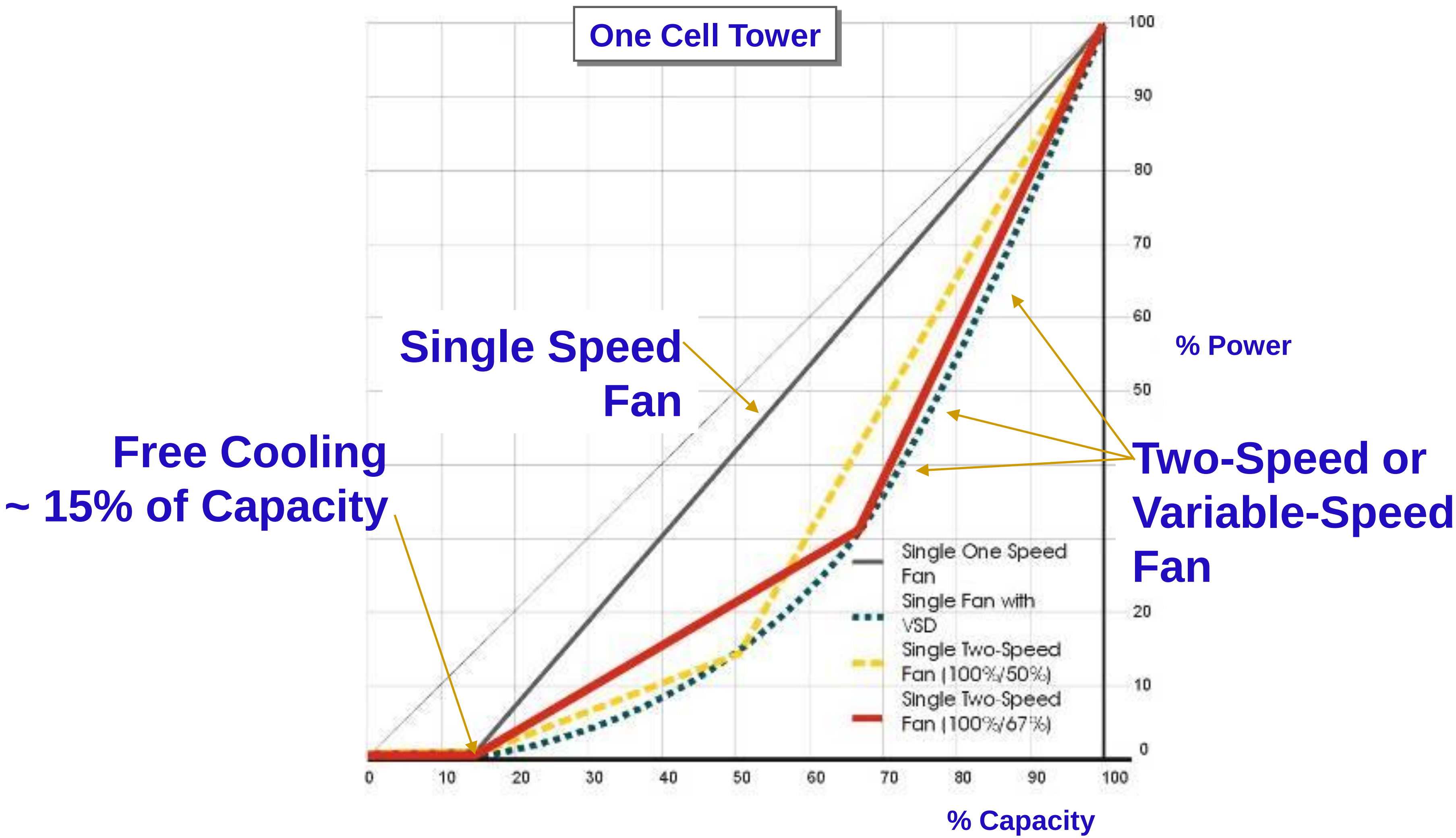
Cooling Towers



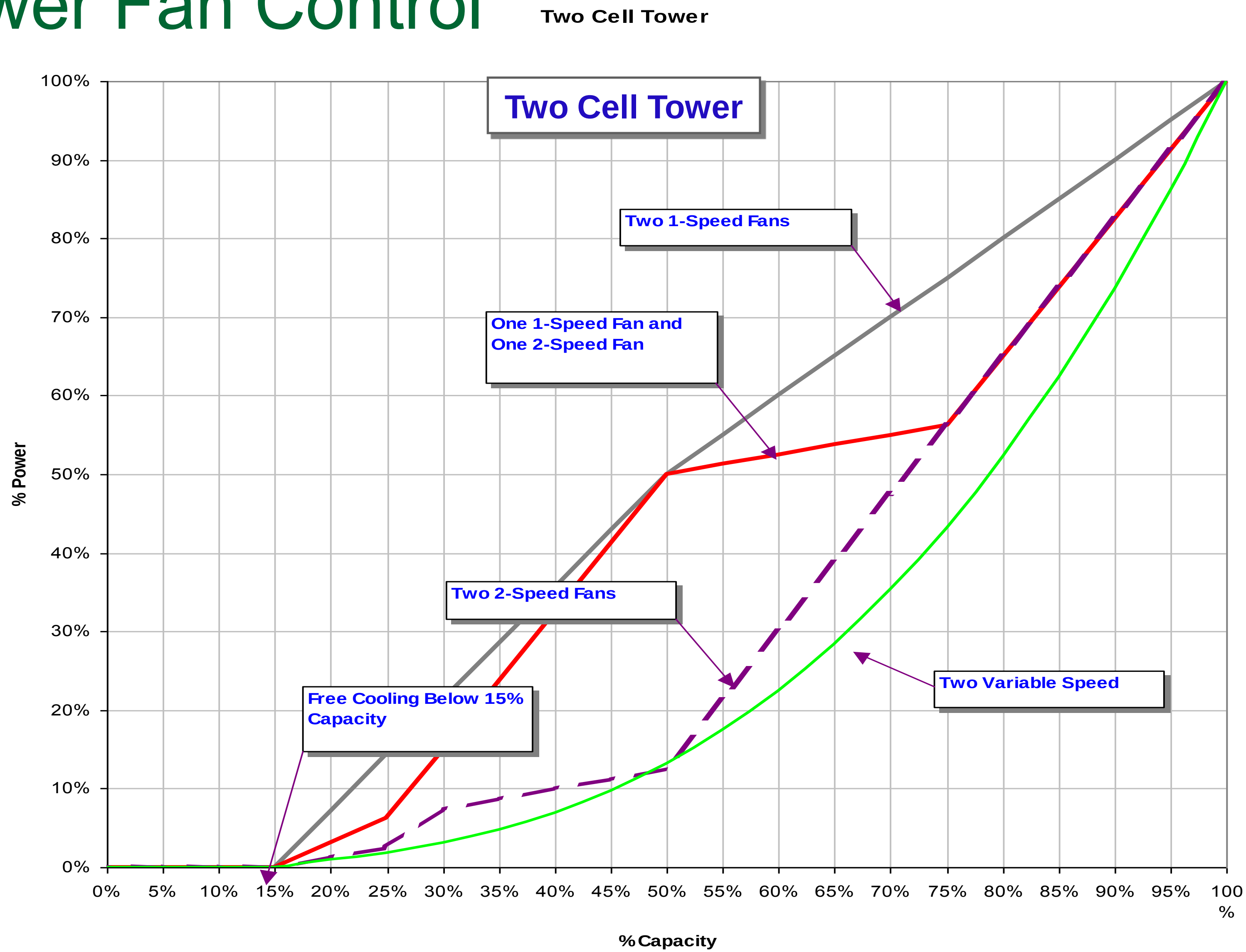
Cooling Towers

- Tower Fan Control
- Tower Efficiency
- Tower Range and Approach

Tower Fan Control



Tower Fan Control



Tower Fan Control

- One-speed control is almost *never* the optimum strategy regardless of size, weather, or application
- Two-speed 1800/900 rpm motors typically best life cycle costs at mid-1990 VSD costs, but…
- VSDs may be best choice anyway
  - Costs continue to fall
  - Soft start reduces belt wear
  - Lower noise
  - Control savings for DDC systems (network card options)
  - More precise control
- Pony motors are more expensive than two-speed but offer redundancy
- Multiple cell towers should have speed modulation on at least 2/3 of cells (required by ASHRAE 90.1)

Tower Efficiency Guidelines

- Use Propeller Fans
  - Avoid centrifugal except where high static needed or where low-profile is needed and no prop-fan options available.
  - Consider low-noise propeller blade option and high efficiency tower where low sound power is required.
- For office and standard commercial occupancies, evaluate oversizing to 50 to 60 gpm/hp at 95 F to 85 F @ 75 F WB
- For data centers and other 24/7 facilities, evaluate oversizing to 80 gpm/hp at 95 F to 85 F @ 75 F WB
- If time is available, do performance bid like the chiller performance bid (discussed later)

Cooling Tower Performance Bid

300,000 ft^2 Office

	ASHRAE 90.1 Efficiency (gpm/hp)	Approach (deg-F)	Total Cost	Tower Cost Rank	Incremental Energy Cost	Incremental LCC vs best LCC	LCC Rank
Manufacturer 1 Option 1	63.9	9.6	$ 47,891	6	$ 1,935	$ 13,211	8
Manufacturer 2 Option 1	43.6	5.0	$ 61,447	14	$ 395	$ 6,899	7
Manufacturer 2 Option 2	49.4	5.6	$ 58,602	12	$ 445	$ 4,699	5
Manufacturer 2 Option 3	43.8	6.9	$ 54,086	9	$ 1,988	$ 20,091	12
Manufacturer 2 Option 4	51.0	7.6	$ 51,455	7	$ 2,247	$ 20,801	13
Manufacturer 2 Option 5	45.8	9.0	$ 47,064	4	$ 2,704	$ 22,305	14
Manufacturer 2 Option 6	77.4	6.1	$ 57,466	11	$ 222	$ 686	2
Manufacturer 2 Option 7	80.6	5.8	$ 60,528	13	$ -	$ 884	3
Manufacturer 3 Option 1	42.6	10.0	$ 41,891	1	$ 2,868	$ 19,248	11
Manufacturer 3 Option 2	62.0	9.0	$ 42,543	2	$ 1,839	$ 6,624	6
Manufacturer 3 Option 3	50.9	8.0	$ 44,950	3	$ 2,491	$ 17,443	9
Manufacturer 3 Option 4	43.4	7.1	$ 47,311	5	$ 2,349	$ 17,973	10
Manufacturer 3 Option 5	60.5	6.1	$ 52,148	8	$ 581	$ -	1
Manufacturer 3 Option 6	45.3	5.0	$ 57,009	10	$ 379	$ 2,255	4

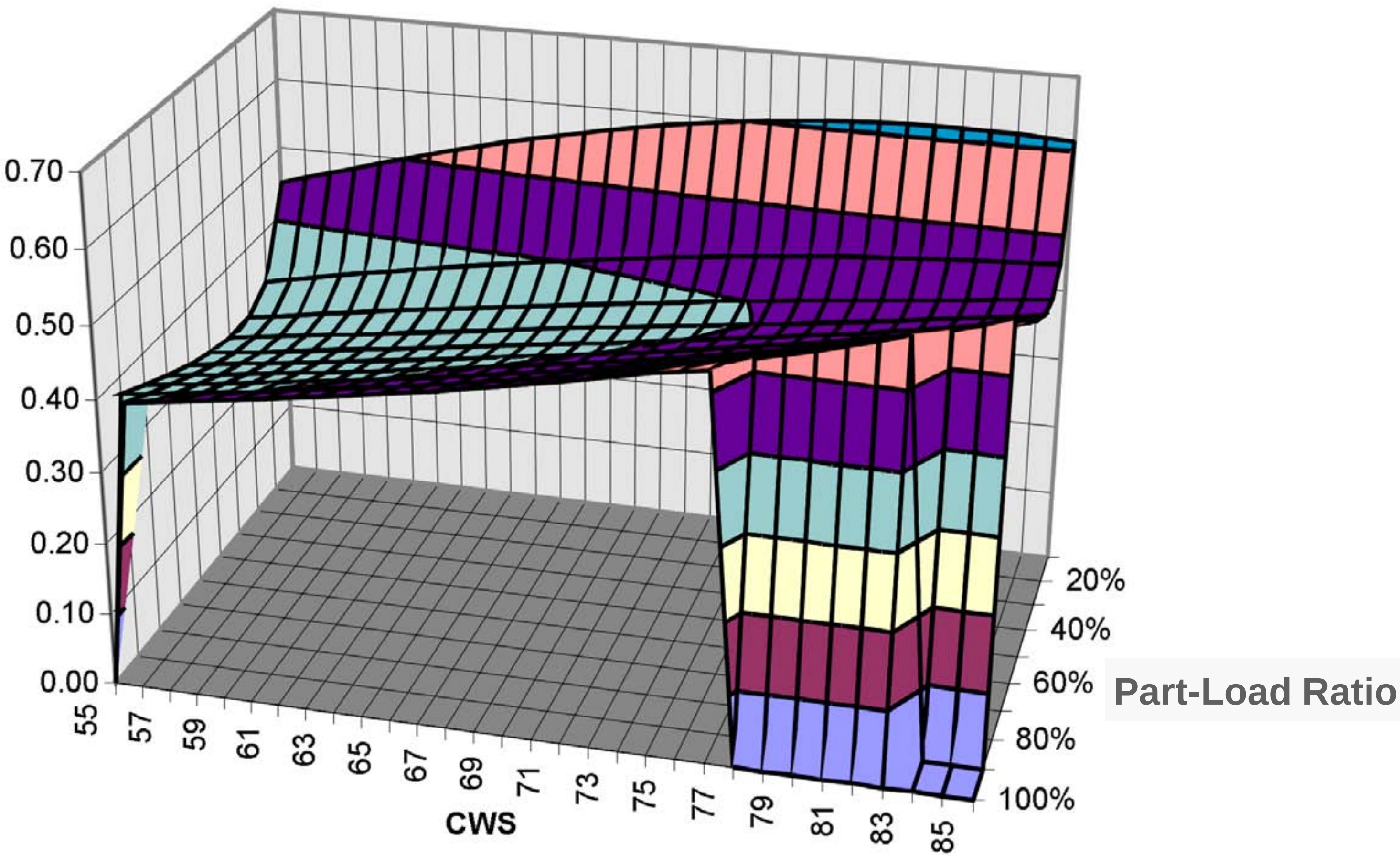
45=>81

5.0=>6.1

Cooling Tower Flow

- For plants with multiple cells and CW pumps, specify towers for low flow capability so that all cells can be active even with only one pump on
  - It is always more efficient to run water through as many cells as possible (due to fan laws with 2-speed or variable speed motors, and to "free" cooling)
  - Turndown usually available as low as 3:1 using low-flow nozzles or weir dams
  - Turndown measures can be immediately cost effective if you can eliminate automatic cell isolation valves

Chillers


0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
55
57
59
61
63
65
67
69
71
73
75
77
79
81
83
85
CWS
20%
40%
60%
80%
100%
Part-Load Ratio

Chiller Procurement

- Standard Approach
  - Pick number of chillers, usually arbitrarily or as limited by program or space constraints
  - Take plant load and divide by number of chillers to get chiller size (all equal)
  - Pick favorite vendor
  - Have vendor suggest one or two chiller options
  - Pick option based on minimal or no analysis
  - Bid the chillers along with the rest of the job and let market forces determine which chillers you actually end up installing

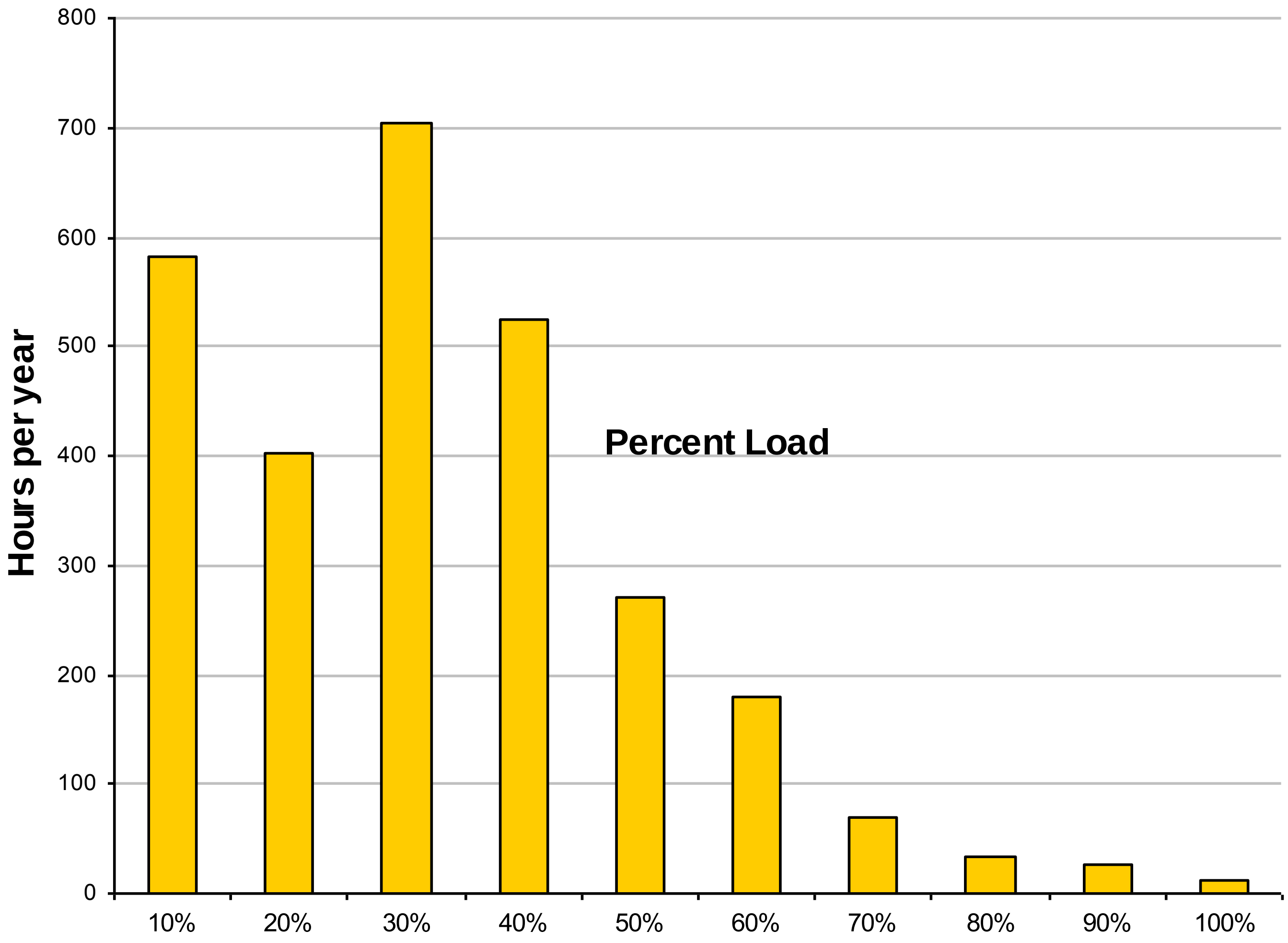
Chiller Procurement

- Recommended Approach
  - Pick a short list of vendors based on past experience, local representation, etc.
  - Request chiller bids based on a performance specification. Multiple options encouraged.
  - Adjust bids for other first cost impacts
  - Estimate energy usage of options with a detailed computer model of the building/plant
  - Select chillers based on lowest life cycle cost

Chiller Bid Specification

- Don't Specify:
  - Number of chillers
  - Chiller size
  - Chiller efficiency
  - Chiller unloading mechanism
  - As much as possible – keep the spec flexible!
- Do Specify:
  - Total design load
  - Anticipated load profile
  - Minimum number of chillers and redundancy requirements
  - Design CHW/CW entering and leaving temperatures and/or flows (or tables of conditions)
  - Available energy sources
  - Physical, electrical or other limitations
  - Acoustical constraints
  - Acceptable refrigerants

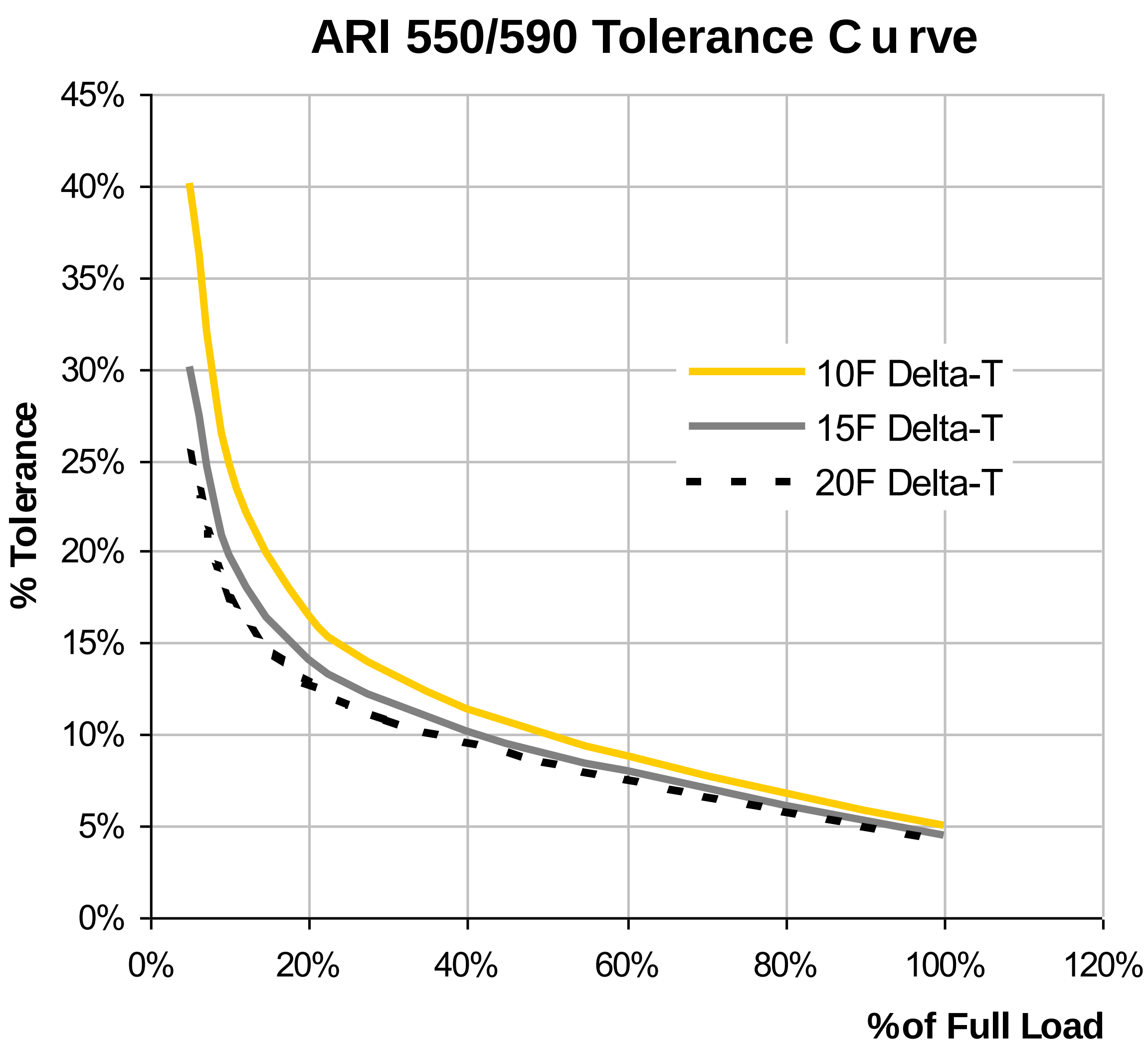
Sample Load Profile



Zero Tolerance Data

- Do NOT Allow Tolerance to be Taken in Accordance with ARI 550/590!
- Why Insist on Zero Tolerance?
  - Levels playing field – tolerances applied inconsistently among manufacturers
  - Modeled energy costs will be more accurate
  - High tolerance at low loads makes chillers appear to be more efficient than they will be, affecting comparison with unequally sized, VFD-driven, or multiple chiller options

Zero Tolerance Data



Factory Tests and Liquidated Damage Clauses

- Certified Factory Tests
  - Need to verify performance to ensure accurate claims by chiller vendors in performance bids
  - Field tests are difficult or impossible and less accurate
  - Last chance to reject equipment
- Liquidated Damage Clause
  - One-time penalty for failing tests as an option to rebuilding or repairing chiller
  - If you don’t have teeth you shouldn’t waste your money on apples

Chiller Bid Form

Complete this worksheet before completing Part Load and Full Load worksheets (some fields are calculated automatically from the data on this sheet

Fill out all yellow-highlighted cells. Others are fixed or calculated automatically

Chiller Performance Form			
Option:			
Manufacturer:			
Model:			
Compressor type:			
Refrigerant:			
Delivery lead time (weeks):			
Operating Constraints			
Maximum CHW flow rate:		Maximum CW flow rate:	
Minimum CHW flow rate:		Minimum CW flow rate:	
Voltage/phase:	480/3	Minimum CW supply temperature:	
Full load amps:			
Design Conditions			
CHW fouling factor:	0.0001	CW fouling factor:	
Leaving CHWST:	42	Entering CWST:	
Entering CHWRT:	59	Leaving CWRT:	
Design CHW flow:		Design CW flow:	
CHW DP (ft):		CW DP (ft):	
Design kW (w/o ARI Tolerance):			
Design capacity:	0	Design kW/ton:	0

Yellow: Fields to be completed by Vendor

White: Fixed fields

Gray: Calculated fields

Chiller Bid Form

Full Load Data						
Please fill in all data on the "Start Here" tab before filling in the table. Please fill in the yellow cells. The capacity and power inputs are for unmodulated operation assuming no power or current limits with all capacity control devices fully open.						
		Evaporator		Condenser		
Capacity	Power	Exit Temp	Flow Rate	Entering Temp	Flow Rate	Exit Temp
tons	kW	°F	gpm	°F	gpm	°F
		43	550	85	700	85
		43	550	75	700	75
		43	550	65	700	65
		43	550	Min = 60	700	60
		45	550	85	700	85
		45	550	75	700	75
		45	550	65	700	65
		45	550	Min = 60	700	60
		50	550	85	700	85
		50	550	75	700	75
		50	550	65	700	65
		50	550	Min = 60	700	60
		43	550	85	400	85
		43	550	75	400	75
		43	550	65	400	65
		43	550	Min = 60	400	60
		45	550	85	400	85
		45	550	75	400	75
		45	550	65	400	65

Chiller Bid Form

Part Load Conditions

Please fill in all data on the "Start Here" tab before filling in the table. Please fill in yellow cells. Where the conditions are beyond the range of the chiller, leave the entry blank. Do not include ARI tolerance in capacity or power listed.

Percent of Design	Capacity tons	Exit Evap °F	Ent Cond °F	Exit Cond °F	P kW	EvapFlow gpm	CondFlow gpm
100%	298	42.0	80.0	92.2	200	550	700
90%	268	42.0	80.0	89.2		550	700
80%	238	42.0	80.0	88.2		550	700
70%	209	42.0	80.0	87.2		550	700
60%	179	42.0	80.0	86.1		550	700
50%	149	42.0	80.0	85.1		550	700
40%	119	42.0	80.0	84.1		550	700
30%	89	42.0	80.0	83.1		550	700
90%	268	42.0	77.5	86.7		550	700
80%	238	42.0	75.0	83.2		550	700
70%	209	42.0	72.5	79.7		550	700
60%	179	42.0	70.0	76.1		550	700
50%	149	42.0	67.5	72.6		550	700
40%	119	42.0	65.0	69.1		550	700
30%	89	42.0	62.5	65.6		550	700
100%	298	42.0	80.0	97.9		550	400
90%	268	42.0	77.5	93.6		550	400
80%	238	42.0	75.0	89.3		550	400
70%	209	42.0	72.5	85.0		550	400
60%	179	42.0	70.0	80.7		550	400
50%	149	42.0	67.5	76.4		550	400
40%	119	42.0	65.0	72.2		550	400

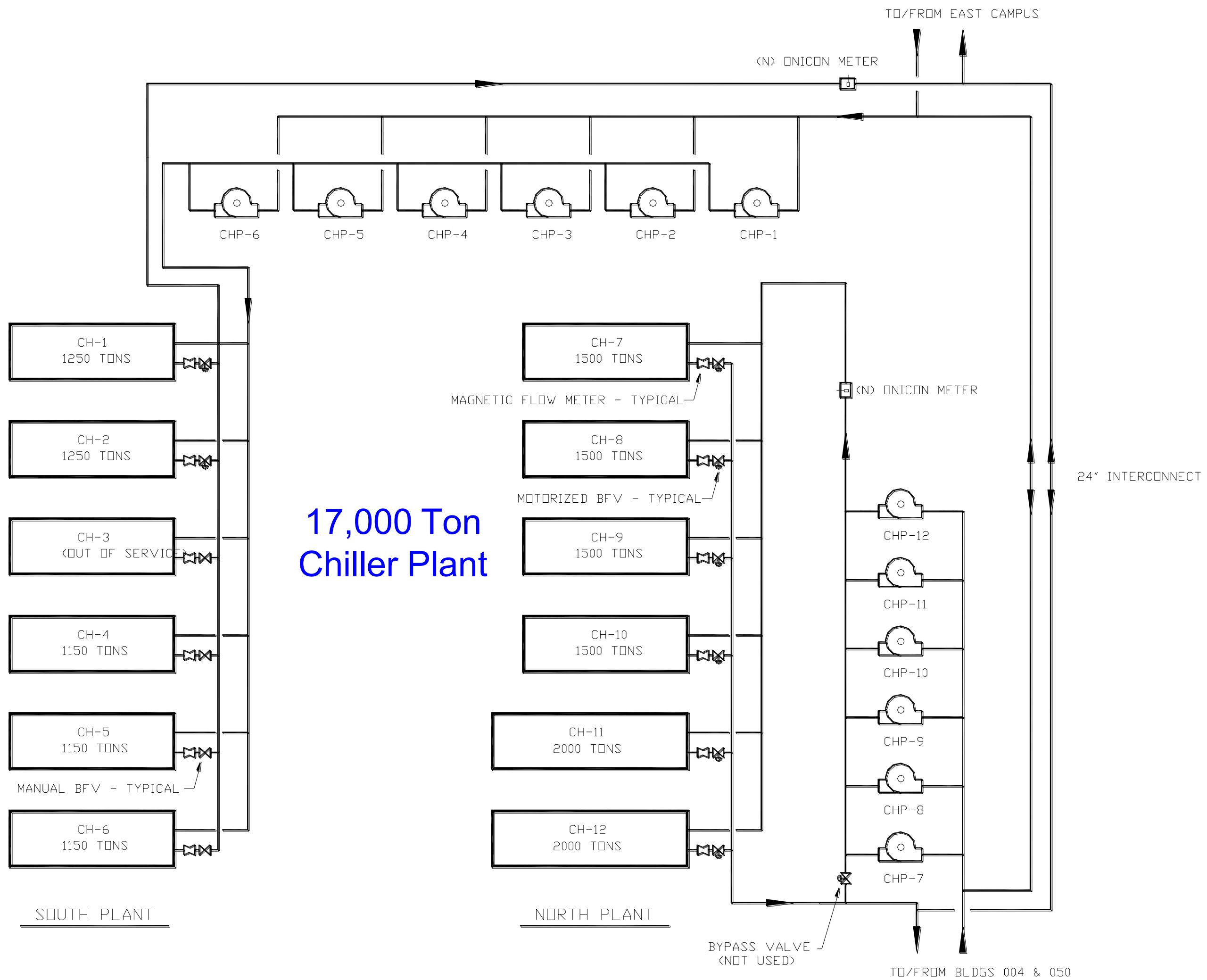
Chiller Bid Evaluation

- Adjust for First Cost Impacts
- Estimate Maintenance Costs
- Calculate Energy Costs
  - DOE-2.1E or DOE-2.2 model of building and plant
- Calculate Life Cycle Costs
- Temper Analysis with Consideration for “Soft” Factors
- Final Selection

Example Projects

- Large Central Plant
  - Central plant serving industrial/office/research park,
    San Jose, CA. 17,000 tons total capacity
- Large High-rise Office Building
  - Office plus small data center, retail,
    San Francisco, CA. 15 stories, 540,000 ft^2

Central Chilled-Water Plant



Chiller Options

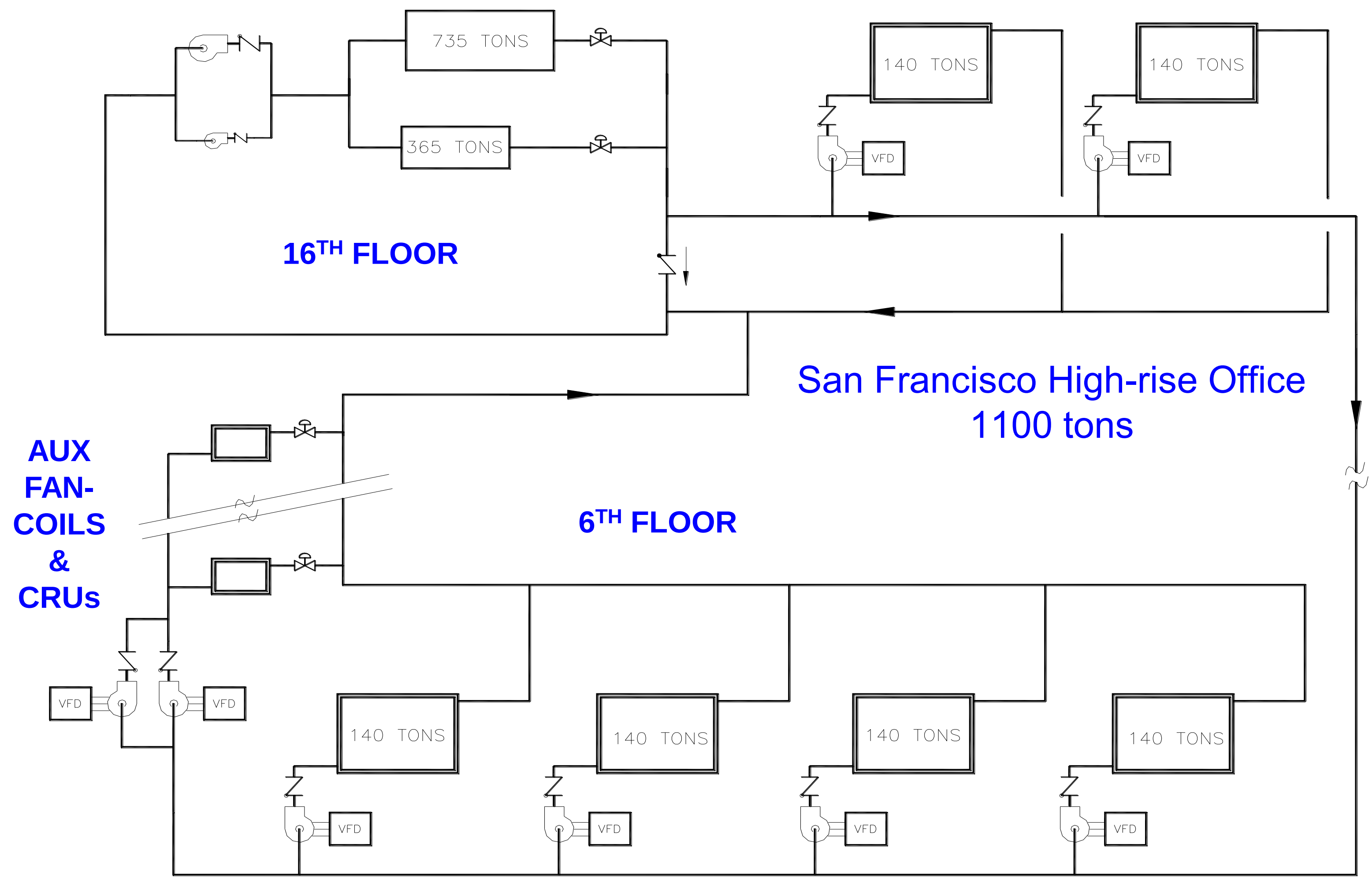
LCC Assumptions:

Discount rate	9%
Electricity Escalation	0%
Analysis years	15

Selected Chillers

	Description	1st Cost Rank	Energy Usage Rank	Life Cycle Cost versus Base	LCC Rank
A #1	Two 1327 tons, 0.57 kW/t	1	5	$0	1
A #2	Two 1421 tons, 0.55 kW/t	2	4	$87,047	4
B #1	Two 1330 tons, 0.56 kW/t	3	3	$9,994	2
C #1	Two 1290 tons, 0.56 kW/t	5	6	$266,804	7
C #2	Two 1284 tons, 0.57 kW/t	4	7	$191,539	6
C #3	Two 1250 tons, 0.53 kW/t	6	2	$53,010	3
C #4	Two 1273 tons, 0.53 kW/t	7	1	$87,894	5

Central Chilled-Water Plant



Central Chilled-Water Plant

Selected Chillers

	Description	1st Cost Rank	Energy Cost Rank	Life Cycle Cost Savings vs Base	LCC Rank
A #1	400 ton, 0.50 kW/t; 700 ton, 0.55 Kw/ton	6	9	$142,016	10
A #2	400 ton w/VFD, 0.50 kW/t; 700 ton, 0.55 Kw/ton	9	2	$22,092	4
B #1	365 ton, 0.56 kW/t; 735 ton, 0.50 kW/t	1	12	$173,962	12
B #2	365 ton w/VFD, 0.56 kW/t; 735 ton, 0.50 kW/t	3	5	$21,246	3
B #3	365 ton w/VFD, 0.56 kW/t; 735 ton w/VFD, 0.50 kW/t	8	4	$7,702	2
C #1	200 ton, 0.50 kW/t; 900 ton dual 0.54 kW/t	2	8	$78,159	5
C #2	550 ton dual, 0.56 kW/t 550 ton dual, 0.56 kW/t	5	11	$141,179	9
C #3	400 ton dual, 0.53 kW/t; 700 ton dual 0.53 kW/t	4	7	$112,419	8
C #4	200 ton, 0.53 kW/t; 350 ton dual 0.57 kW/t; 550 ton dual 0.59 kW/t	7	10	$147,440	11
D #1	550 ton w/VFD , 0.49 kW/t; 550 ton, 0.48 kW/t	11	6	$104,078	7
D #2	300 ton w/VFD , 0.50 kW/t; 800 ton, 0.48 kW/t	10	1	$0	1
D #3	365 ton w/VFD , 0.52 kW/t; 366 ton, 0.51 kW/t 366 ton, 0.51 kW/t	12	3	$92,421	6

LCC Assumptions:

Discount rate	8%
Electricity Escalation	0%
Analysis years	15

Considering "Soft Factors"

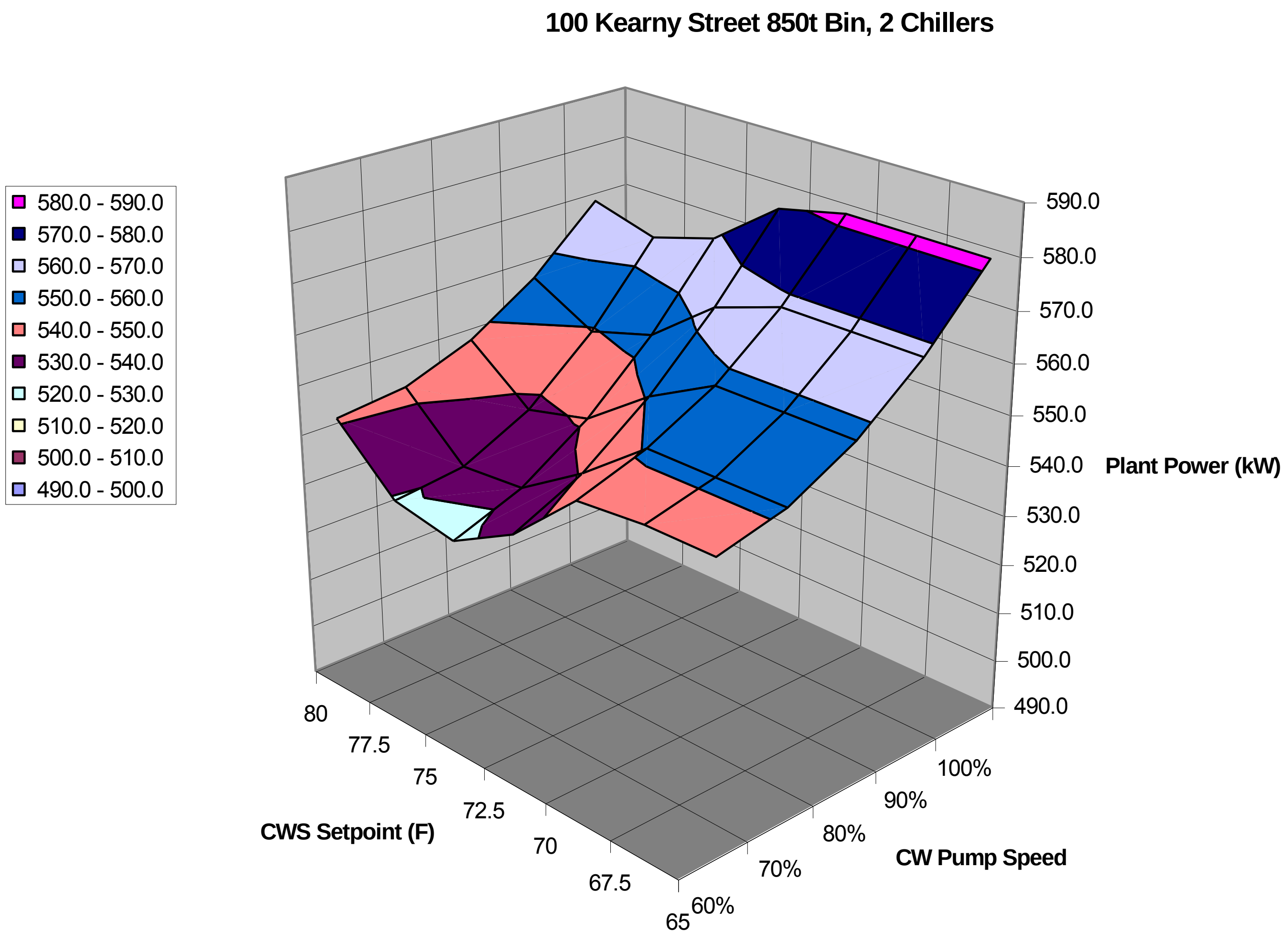
- Why Option B3 was Selected over Option D2:
  - Close in LCC (2nd behind Option D2) – within the margin of error in the analysis
  - Option B3 used R134a which was preferred by client due to zero ODP (D2 used R-123)
  - Both Option B3 chillers had VSDs (only one in Option D2)
  - Small chiller pump can operate large chiller (flow minimum/design ranges overlap)
  - Option B3 hermetic, Option D2 is open-drive
  - Option B3 had lower first cost

Advantages & Disadvantages

OF RECOMMENDED CHILLER SELECTION APPROACH

- Disadvantages
  - Extra work for both engineer and vendor
  - Difficult to include maintenance impact
  - Assumes energy rate schedules will remain as they are now with simplistic adjustments for escalation
- Advantages
  - Allows manufacturers to each find their own "sweet" spots, both for cost and efficiency
  - Usually higher energy efficiency
  - More rational than typical selection approaches

Optimizing Controls



Optimizing Control Sequences

- Cookbook Solution
  - Staging Chillers
  - Controlling Pumps
  - Chilled Water Reset
  - Condenser Water Reset
- Simulation Approach
- Sample Retrofit Project

Staging Chillers

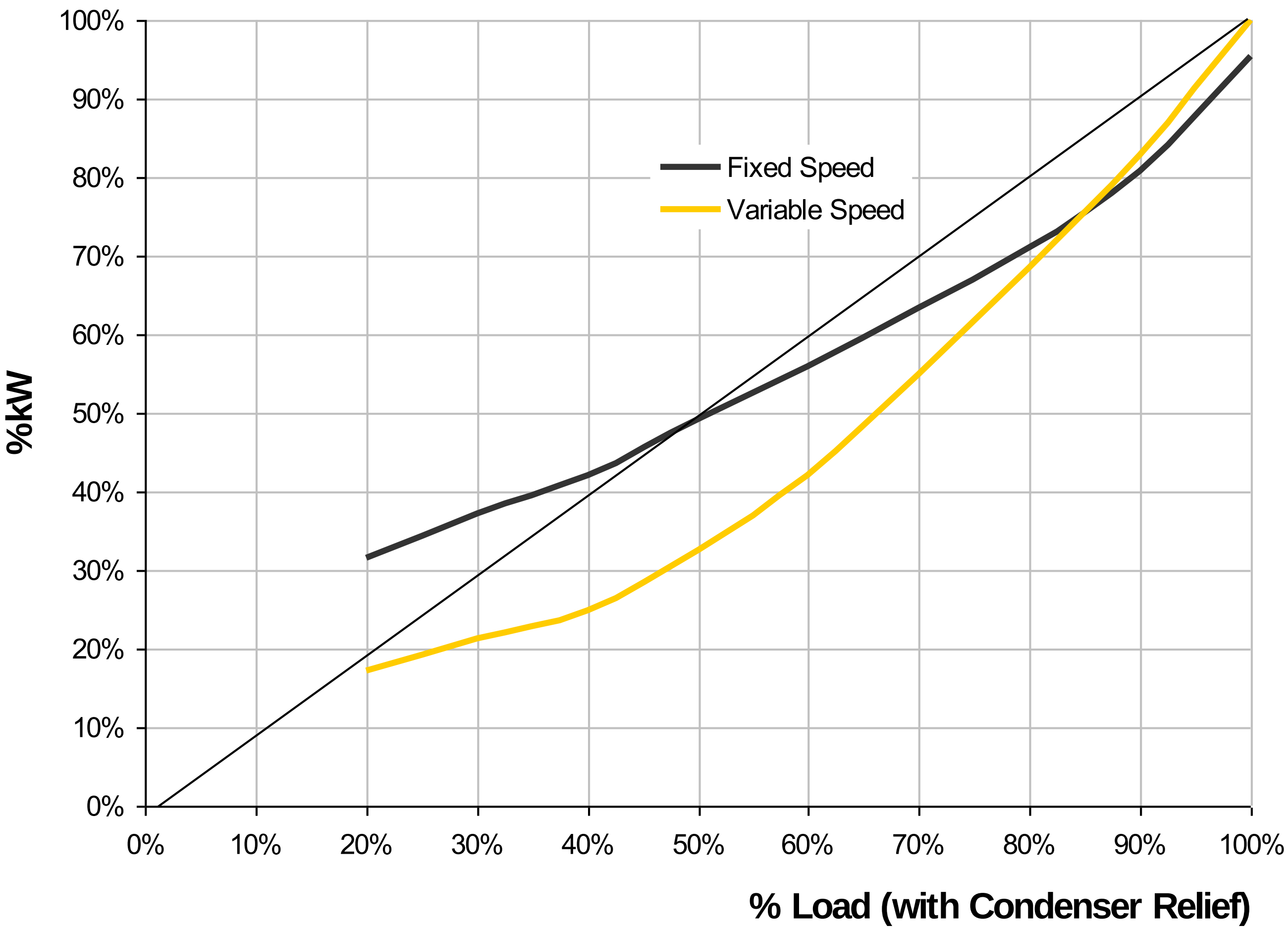
- Fixed Speed Chillers
  - Operate no more chillers than required to meet the load
  - Stage on when operating chillers maxed out as indicated by measured load (GPM, ΔT), CHWST, flow, or other load indicator.
  - For primary-secondary systems w/o check valve in the common, start chiller to ensure P-flow > S-flow
  - Stage off when measured load/flow indicates load is less than operating capacity less one chiller – be conservative to prevent short cycling

Staging Chillers, continued

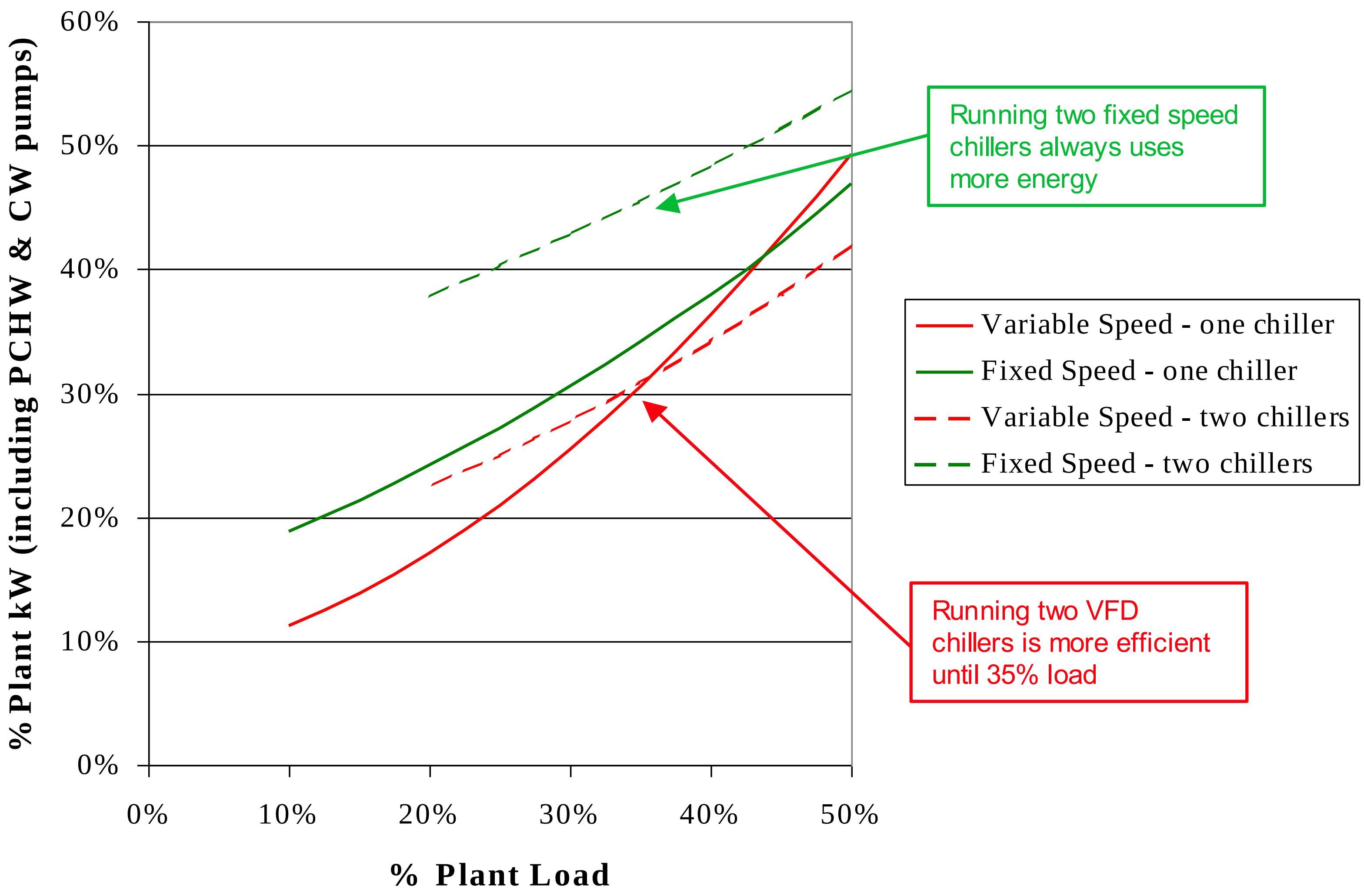
- Variable Speed Chillers
  - Operate as many chillers as possible provided load on each exceeds 30% to 40% load (actual value can be determined by simulation)
  - Energy impact small regardless of staging logic
  - You MUST use condenser water reset to get the savings

Part Load Chiller Performance

w/ Zero ARI Tolerance



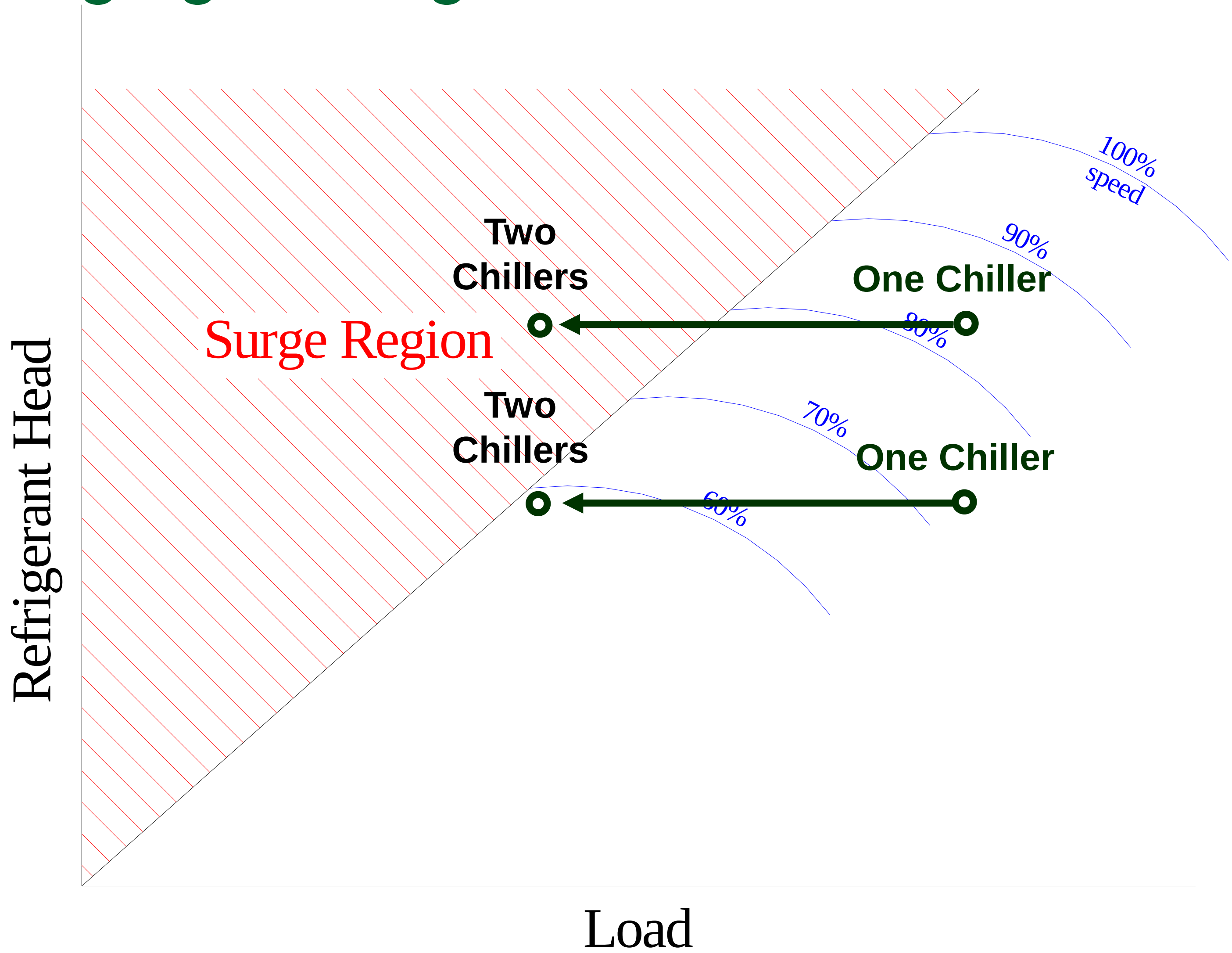
Two-Chiller Plant Performance at Low Load



Cautionary Notes

- Some variable speed chillers don't dynamically measure surge conditions
  - You will lose some of the savings with primary-only variable flow systems because minimum speed may have to be increased to avoid surge
  - You may have premature tripping due to onset of surge otherwise
  - This is only an issue with variable evaporator flow systems (like primary-only variable flow)

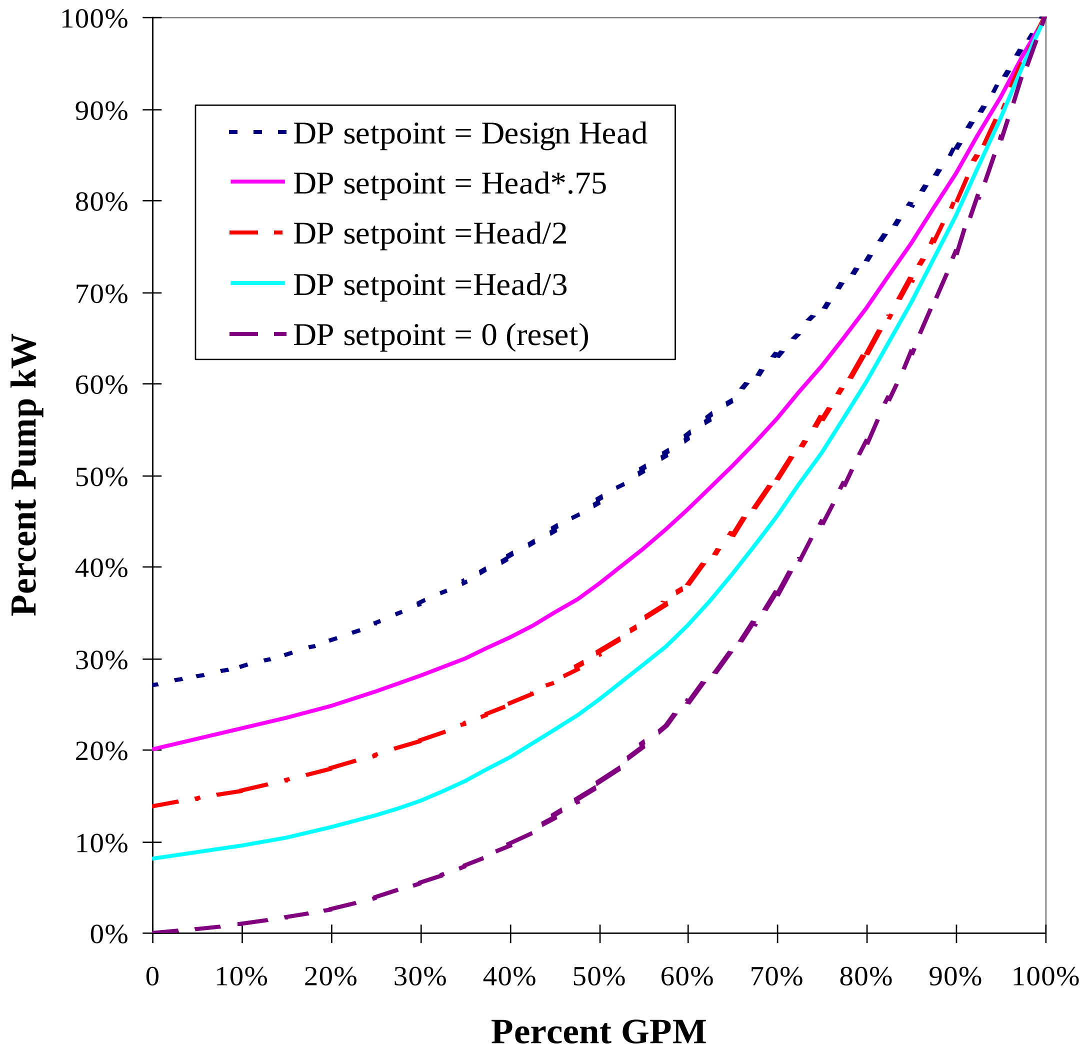
Staging & Surge



Controlling Pumps

- For P/S Systems, Stage Primary CHW Pumps Along With Chillers
- Stage CW Pumps Along with Chillers
  - Evaluate also using one less pump than chillers
- Primary-only and Secondary CHW Pumps
  - Control speed by differential pressure measured as far out in system as possible and/or reset setpoint by valve demand
  - Stage pumps by differential pressure PID loop signal:
    - Start lag pump at ~90% speed (verify limit of pump curve)
    - Stop lag pump at ~40% speed
    - For large HP pumps, determine setpoints with detailed energy analysis

VSD Pump Power vs. Setpoint



Chilled Water Setpoint Reset

- Reset Impacts
  - Resetting CHWST upwards reduces chiller energy but will increase pump energy in VSD variable flow systems
  - If done with “open” or indirect control loops, reset can starve coils and reduce dehumidification
- Recommendations
  - Use reset for constant volume CHW distribution systems
    - Reset based on maximizing one valve position is best strategy – need valve feedback via DDC system
    - Little or no impact on humidity control
  - For VFD variable flow systems, do not reset CHWST
    - Little net savings due to pump energy increase
    - Reset can conflict with DP setpoint reset – too complex
    - Exception for primary-only variable flow systems where you can use reset to keep the bypass valve closed

Condenser Water Setpoint Reset

- Optimum Strategy Cannot Easily Be Generalized
  - Depends on efficiency/sizing of tower and type of chiller
- Recommendations
  - Use chiller manufacturer's optimization controls if available at reasonable price
  - Otherwise use the following (setpoint rules-of-thumb in parentheses):
    - For two speed towers, use low setpoint for low speed (as low as manufacturer recommends) and high setpoint for high speed (equal to design CWST for multi-stage centrifugals and screw; equal to design WB temperature for other centrifugals).
    - For VFD-driven towers, CWS reset by plant load (from as low as manufacturer recommends at 30% plant load up to design CWST at 70% load).
    - Simulate plant to determine best setpoints
    - Reset based on wet-bulb is usually not effective
    - In general never run fans above ~90% speed unless you are losing the load

Optimizing Setpoints through Simulation

- Perform an array of simulations
  - Simulate a range of condenser water set points (e.g. 65-80°F in 2.5°F increments)
  - Simulate as range of allowable condenser water flows (e.g. 40% to 100% in 10% increments)
  - Simulate all possible combinations of number of chillers and number of CW pumps
  - Run as many tower cells as you can based on flow limits
- Determine optimum performance by load bin or combination of fixed set points
- This process is described in upcoming ASHRAE Journal Article (June 2007)

Retrofit Control Analysis Example

Optimum Operating Point